증기발생기 나선형 전열관의 프레팅 마모 특성

Fretting-wear Characteristics of Steam Generator Helical Tubes

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(2004년 1월 9일 접수 : 2004년 3월 9일 심사완료)

Key Words : Steam Generator(증기발생기), Helical Tube(나선형 전열관), Fretting-wear(프레팅 마모), Natural Frequency(고유진동수), Mode Shape(모드 형상), External Pressure(외압)

ABSTRACT

This study investigates the safety assessment of the potential for fretting-wear damages caused by foreign object in operating nuclear power plants. To get the natural frequency, corresponding mode shape and participation factor, modal analyses are performed for the helical type tubes with various conditions. The wear rate of helical type tube caused by foreign object is calculated using the Archard formula and the remaining life of the tube is predicted, and discussed in this study is the effect of the vibration of the tube on the remaining life of the tube. In addition, addressed is the effect of the external pressure on the vibration and fretting-wear characteristics of the tube.

요 약

본 연구에서는 가동중인 원자력발전소의 이물질에 의한 프레팅 마모 특성을 평가하였다. 다양한 조건의 나선형 튜브 고유진동수 및 모드 형상을 구하기 위하여 모드 해석을 수행하였다. 이물질에 의한 나선형 튜브의 마모율을 Archard 공식을 이용하여 계산하였고 이로부터 튜브의 잔여 수명을 예측하였으며 튜브의 진동 특성이 잔여 수명에 미치는 영향을 고찰하였다. 또한 튜브에 가해지는 외압이 진동 및 프레팅 마모 특성에 미치는 영향을 평가하였다.

1. Introduction

Various advanced types of nuclear power reactors are currently under development worldwide, and some of them are ready for construction. One beneficial advantage of the advanced type of reactor is the easy implementation of advanced design concepts and technology. Drastic safety enhancement can be achieved by adopting inherent safety characteristics and passive safety features. Economic improvement is pursued through system simplification, modularization and reduction in the construction time.

SMART(system-integrated modular advanced reactor), a small sized integral type PWR is one of those advanced types of reactors, which is being developed in Korea. It contains all major primary components in a single pressurized vessel. The in-vessel self-controlling pressurizer is one of the advanced design features. The system pressure is passively adjusted by partial pressure of steam and

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nitrogen gas filled in the pressurizer in accordance with variation in pressure and temperature of the primary coolant. Control element drive mechanism has a very fine-step maneuvering capability to compensate the core reactivity change caused by fuel depletion during a normal operation. The modular type once- through SG (steam generator) has an innovative design feature with helically coiled tubes to produce superheated steam at normal operating condition.

There are twelve identical SG cassettes which are located on the annulus formed by the reactor pressure vessel and the core support barrel. Each SG cassette is of once-through design with a number of helically coiled tubes. The primary reactor coolant flows downward in the shell side of the SG tubes, while the secondary feedwater flows upward in the tube side.

The helical type tubes adopted for SMART may have a totally different behavior from that of U-tubes which are used in typical PWR.[1,2] It necessitates a study on the fretting-wear prediction including vibration characteristics to assure the structural integrity of the helically coiled tubes during a normal operation.

Therefore, this study investigates the fretting-wear characteristics of steam generator helical tubes. Modal analyses are performed for the finite element modelings of tubes with various conditions. The effects of coil diameter and the number of turns etc on the modal and fretting-wear characteristics of tubes, which are expressed in terms of the natural frequency, corresponding mode shape, and time required to wear the tube are investigated. Also, addressed in this study is the effect of the external pressure on the vibration and fretting-wear characteristics of the tube.

2. Analysis

2.1 Modal Analysis

Modal analyses using a commercial computer code ANSYS 7.0[3] are performed to find the vibration characteristics of the tube. Several different kinds of finite element models are developed according to the coil diameter, full height, the number of turns (helix angle) and the number of support points (Table 1).

Finite element models are developed using the elastic straight pipe elements (PIPE16) for the helical tube and 3-D point-to-point contact elements (CONTAC52) between support and tube. PIPE16 is a uniaxial element with tension- compression, torsion, and bending capabilities. CONTAC52 represents two surfaces which may maintain or break physical contact and may slide relative to each other. The element is capable of supporting only compression in the direction normal to the surfaces and shear (Coulomb friction) in the tangential direction. The finite element model consists of 1280 PIPE16 elements for the helical tube and 65 CONTAC52 elements between support and tube for 8 support points of Type A as shown in Fig. 1.

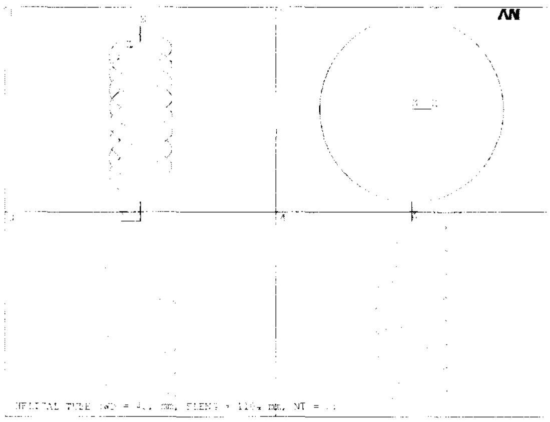
The boundary conditions at the two ends of the tube are fixed. To simulate the nodes of the tube at the support locations to be free to move in the longitudinal direction, contact elements are used between support and corresponding tube locations with the support node fixed.

The Block Lanczos method is used for the eigenvalue and eigenvector extractions to calculate 50 natural frequencies, which were chosen

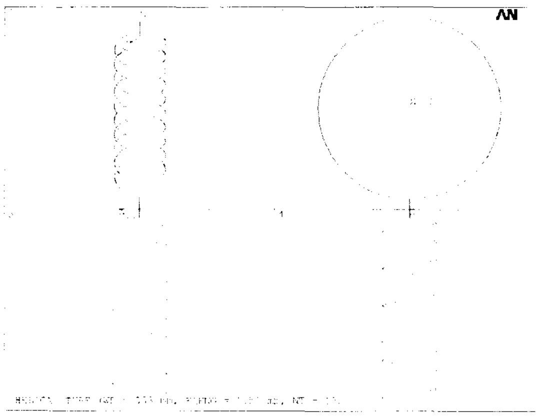
Table 1 Geometric description of helical tubes

Parameter (mm)	Type A	Type B	Type C	Type D	Type E
Wire diameter	10				
Wire thickness	1.5				
Coil diameter	422	338	282	198	142
Full height	1104	1150	1104	1104	1150
Number of turns	8	10	12	16	25

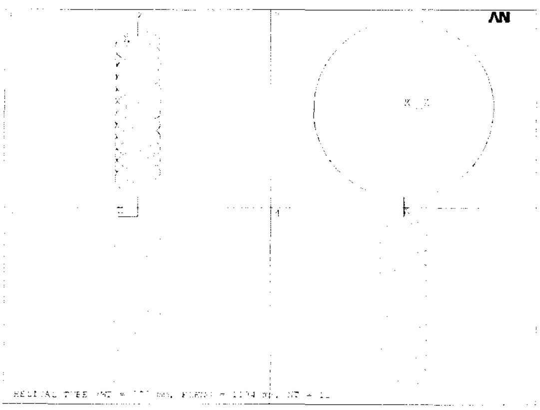
considering cumulative mass fraction. It uses the Lanczos algorithm where the Lanczos recursion is as accurate as the subspace method, but faster. The Block Lanczos method is especially powerful when performed with a block of vectors. This method is searching for eigenfrequencies in a given part of the eigenvalue spectrum of a given system. The convergence rate of the eigenfrequencies will be about the same when extracting modes in the midrange and higher end of the spectrum as when extracting the lowest mode.



(a) Type A



(b) Type B



(c) Type C

Fig. 1 Finite element model of helical tubes

2.2 Fretting-wear Prediction

Connors[4] investigated various ways of evaluating and correlating tube wear to tube motion and showed that the Archard's equation[5] for adhesive wear can be applied to fretting-wear as well as continuous sliding conditions.

$$V = K \cdot F_n \cdot L \tag{1}$$

where V = volume of wear generated, K = wear coefficient, F_n = normal forces between surfaces and L = total sliding distance. While wear is not theoretically well defined and the Archard's equation is semi-empirical, it has been proved valuable in practical situations. Rubbing motion caused more wear than impacting motion, so Archard's equation can be used to evaluate tube wear due to foreign objects as well as between tube and tube support. Wear coefficients are shown in Fig. 2 for various material combinations from some experimental data.[6]

The sliding distance can be calculated with the tube vibration amplitude due to the flow-induced vibration and the tube frequency. The sliding distance per second is four times the product of the tube vibration amplitude and the tube frequency and is calculated as[5]:

$$D = 4 \cdot C^* \sqrt{\left(\sum_{m=1}^{n} f_m \cdot d_{m,x} \cdot PF_{m,x}\right)^2 + \left(\sum_{m=1}^{n} f_m \cdot d_{m,y} \cdot PF_{m,y}\right)^2 + \left(\sum_{m=1}^{n} f_m \cdot d_{m,z} \cdot PF_{m,z}\right)^2} \tag{2}$$

where D = sliding distance per second, f_m = m th modal natural frequency of the steam generator tube, $d_{m,x}$ = modal displacement of mode m in x -direction, $d_{m,y}$= modal displacement of mode m

in y-direction, $d_{m,z}$ = modal displacement of mode m in z-direction, $PF_{m,x}$ = modal participation factor of mode m in x-direction, $PF_{m,y}$ = modal participation factor of mode m in y-direction, $PF_{m,z}$ = modal participation factor of mode m in z-direction, and n is the sufficient number of modes that should be considered. Also, C^* is the factor which relates the root mean square (RMS) deflection from test or analysis to the amplitude of the modal analysis for a steam generator tube as follows:

$$RMS = C^* \sqrt{\left(\sum_{m=1}^{n} d_{m,x} \cdot PF_{m,x}\right)^2 + \left(\sum_{m=1}^{n} d_{m,y} \cdot PF_{m,y}\right)^2 + \left(\sum_{m=1}^{n} d_{m,z} \cdot PF_{m,z}\right)^2} \tag{3}$$

Therefore the total sliding distance L in time t is determined from Eqs. (2) and (3):

$$L = 4t \cdot RMS \cdot \frac{1}{\psi} \tag{4}$$

where

$$\psi = \sqrt{\frac{\left(\sum_{m=1}^{n} d_{m,x} \cdot PF_{m,x}\right)^2 + \left(\sum_{m=1}^{n} d_{m,y} \cdot PF_{m,y}\right)^2 + \left(\sum_{m=1}^{n} d_{m,z} \cdot PF_{m,z}\right)^2}{\left(\sum_{m=1}^{n} f_m \cdot d_{m,x} \cdot PF_{m,x}\right)^2 + \left(\sum_{m=1}^{n} f_m \cdot d_{m,y} \cdot PF_{m,y}\right)^2 + \left(\sum_{m=1}^{n} f_m \cdot d_{m,z} \cdot PF_{m,z}\right)^2}} \tag{5}$$

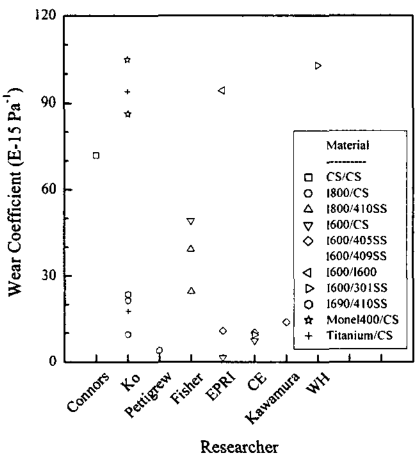


Fig. 2 Wear coefficients for various material combinations

The wear volume generated on the tube is calculated using Eqs. (1) and (4) as

$$V = 4Kt \cdot RMS \cdot F_n \frac{1}{\psi} \tag{6}$$

The tube depth associated with this wear volume can be determined by defining the geometry of the wear scar. The geometrical relationship between wear volume and wear depth for a SG tube in contact with a flat bar is shown in Fig. 3. Assuming that the tube and flat bar are perfectly aligned, the wear scar volume, V_s, is simply the area of interaction of a straight line and a circle of radius, R, multiplied by the flat bar width, l

$$V_s = \frac{R^2 l}{2}[2\alpha - \sin(2\alpha)] \tag{7}$$

where α is the contact angle (rad) and there is relation between the tube radius R and the wear depth h as

$$\alpha = \cos^{-1}\left(1 - \frac{h}{R}\right) \tag{8}$$

Equating the wear volume generated to the geometrically defined wear volume, the relationship between wear depth and time can be defined. The time required to wear into a tube to the minimum acceptable wall thickness h, which is usually defined as 40 % through wall, is calculated from Eqs. (6) and (7) as :

$$t = \frac{R^2 l \psi}{8KF_n \cdot RMS}[2\alpha - \sin(2\alpha)] \tag{9}$$

Equation (9) was derived based on the assumptions that the foreign object will remain in the same location once the tube wear begins and that only the tube will experience the wear. This can be used to calculate the time required to wear completely through the tube wall. It should be noted that the tube could fail in fatigue before complete wear-through occurs.

3. Results and Discussion

Modal analyses for several kinds of finite element models are performed and their results are summarized and typical mode shapes are shown in Fig. 4.

Five different types of helical tubes as shown in Table 1 are chosen to investigate the fretting-wear characteristics. Modal analyses are performed and their natural frequency summaries are shown in Fig. 5.

The variation of the frequencies versus the number of turns is given in Fig. 6. As the number of turns increases with the same height maintained, the total length of the tube increases and the stiffness of the system decreases when all the other properties are kept the same. The frequencies except for the first several modes are reduced and this is particularly pronounced in the higher modes.

To investigate the effect of the coil diameter on the vibration characteristics of the tube, different diameters are input for Type A. The resulting natural frequencies and their normalized values with respect to the coil diameter of 422 mm are shown in Figs. 7 and 8, which indicate that increasing coil diameter decreases the system stiffness which in turn decreases the frequencies. As the coil diameter is increased, the frequencies get closer each other and coupled modes begin to appear. The normalized natural frequencies can be represented for all modes as;

$$\lambda = 30.70 \cdot \exp\frac{-WD}{93.35} + 0.6733 \qquad (10)$$

where λ and WD are the normalized natural frequency and the coil diameter (mm), respectively.

Not like the steam generator U-tubes of typical PWR, the primary side of the coolant flows outside of the tube in SMART and therefore pressure inside of the tube is lower than that of outside. To investigate the effect of the external pressure on the vibration characteristics of the tube, pressure is input as surface load on the element surface of Type A. The resulting natural frequencies are shown in Fig. 9, which indicate that the natural frequency changes are negligible up to about 1000 MPa of the external pressure. Above this pressure, the natural frequencies of some modes jump very rapidly with the increase of the pressure. Considering that the pressure difference during a normal operation of the nuclear power plant is almost 10 MPa, the natural frequency difference can be concluded to be negligible with the inclusion of the pressure. Therefore the effect of external pressure on the remaining life of the tube due to foreign object is expected to be negligible during a normal operation of the nuclear power plant up to the external pressure of about 100 MPa.

ψ defined in Eq. (9) is calculated and summarized in Fig. 10 for five different types of tube from modal analyses results at node 326 where the foreign object is assumed to rest on. Because the time required to wear is proportional to ψ, the remaining life of helical tube with smaller coil diameter decreases significantly comparing that with larger diameter for the same flow velocity (Figs. 10 and 11). It should be noted that tube Type A which has the largest coil diameter has the longest life from the standpoint of fretting-wear even though it was the worst for the fluidelastic instability point of view.[7] For the same situation the helical tubes located in the inner space have smaller coil diameter and experience more fretting-wear than those located in the outer space with larger coil diameter. Therefore it is recommended

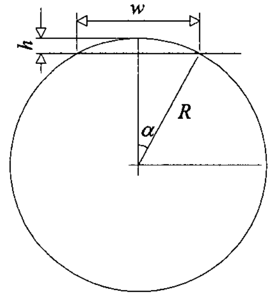


Fig. 3 Contact between tube and flat bar

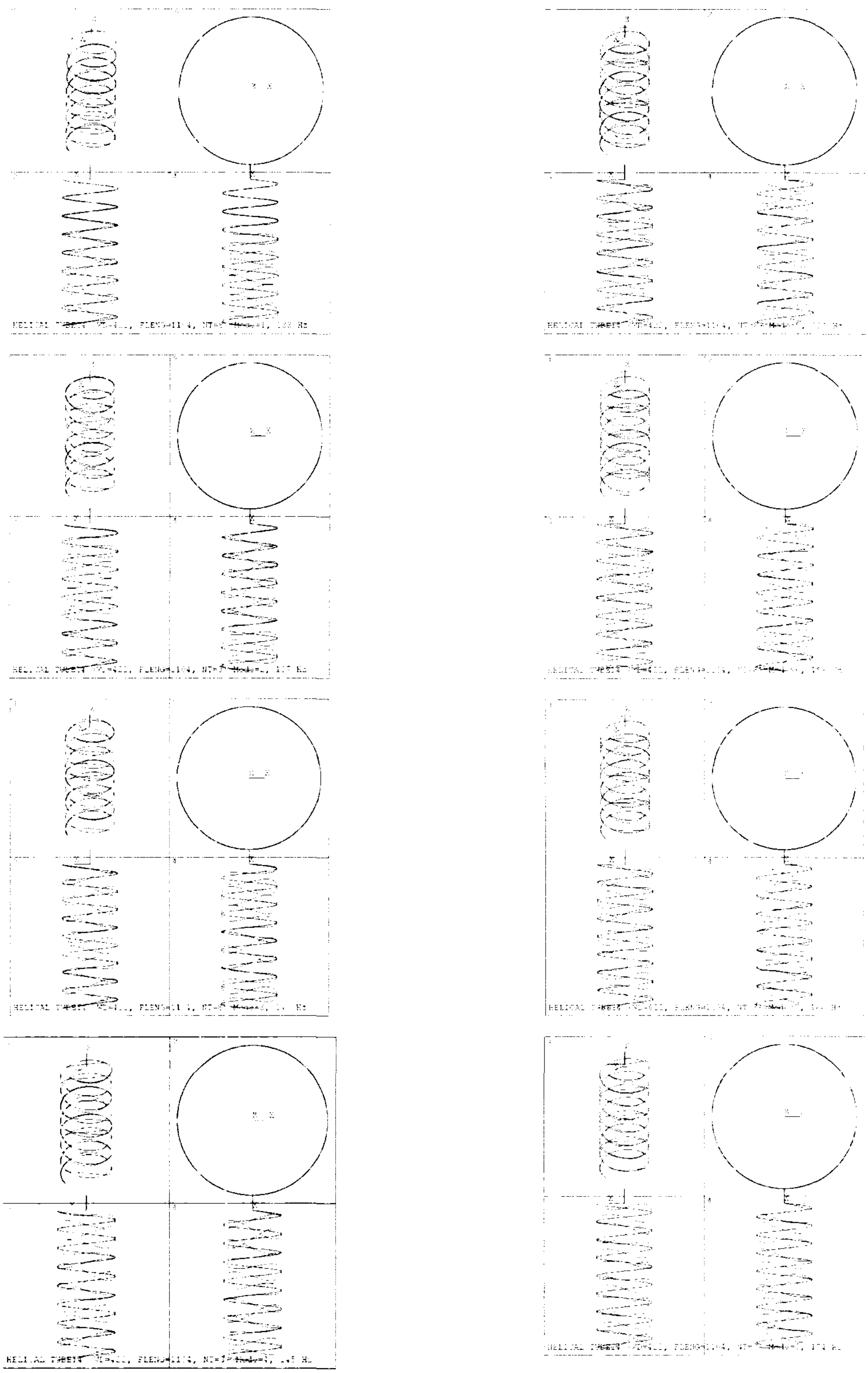


Fig. 4 Typical mode shapes of tube with 4 supports

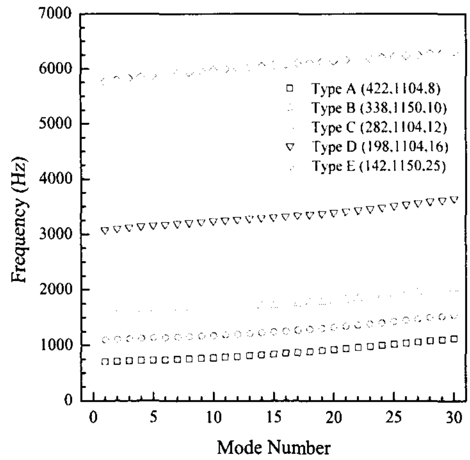


Fig. 5 Natural frequencies for each tube type

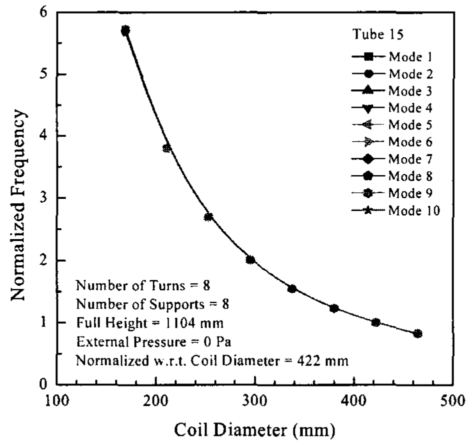


Fig. 8 Normalized natural frequency variations with respect to the coil diameter

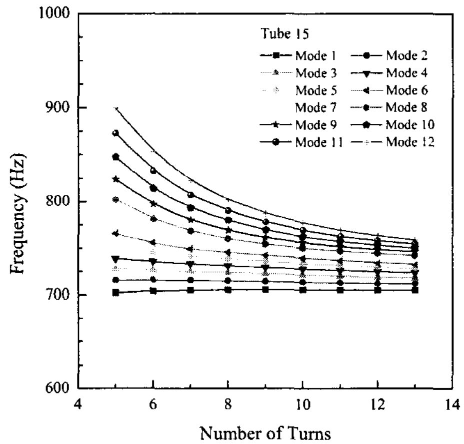


Fig. 6 Natural frequency variations with respect to the number of turns

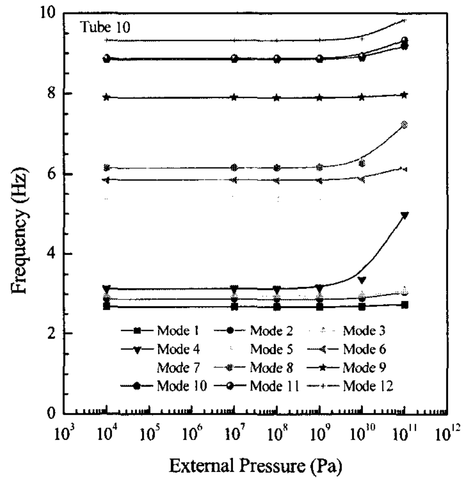


Fig. 9 Natural frequency variations with respect to the external pressure

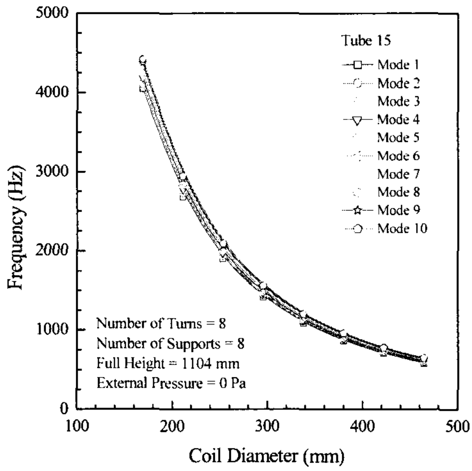


Fig. 7 Natural frequency variations with respect to the coil diameter

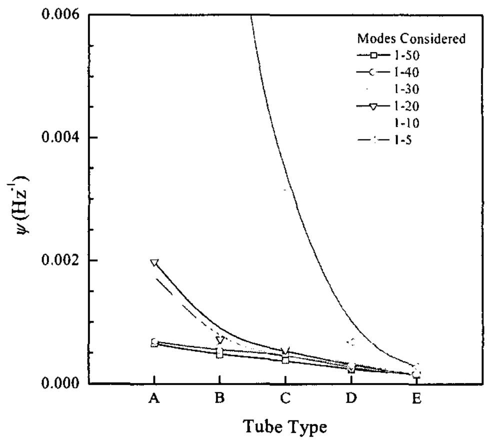


Fig. 10 ψ according to the tube type

that actions such as special design or inspection to keep foreign object from remaining in the inner space of SG cassette should be taken.

Figures 10 and 11 show ψ with respect to the total number of modes under consideration, which show that in calculating ψ sufficient number of modes should be considered not to overestimate the remaining life of the tube.

Also, from Eq. (9) the time required to wear is proportional to the contact angle a by $[2\alpha - \sin(2\alpha)]$, and their relations are shown in Fig. 12. This can be expected from the fact that wide wear area is generated as a wear develops, and therefore more time is required to wear out the tube.

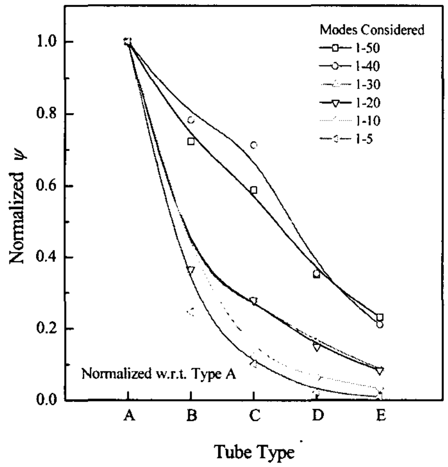


Fig. 11 Normalized ψ according to the tube type

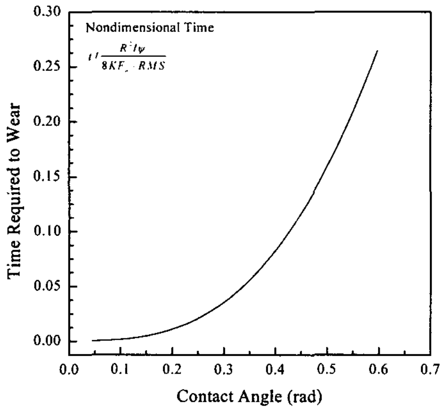


Fig. 12 Time required to wear vs. contact angle

4. Conclusions

To investigate the vibration characteristics of helical tube, modal analyses for various conditions such as coil diameter, the number of turns and the number of supports etc are performed. Derived in this study is the formula to predict the remaining life of the tube which is subject to fretting-wear by a foreign object. The time required to wear the tube is calculated based on the Archard's equation and several parameters are investigated for the effect on the life of the tube.

Based on the analyses performed, the following conclusions were generated;

(1) With increasing coil diameter and the number of turns, the natural frequencies decrease and the changes are much more affected by the coil diameter than the number of turns.

(2) The natural frequency changes of the tube are negligible with the inclusion of the external pressure during a normal operation and therefore it can be concluded that fretting-wear characteristics are not affected by the external pressure.

(3) Sufficient number of modes should be considered to calculate the time required to wear the tube.

(4) Type E is the worst tube for the fretting-wear point of view.

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